Tickling the CMB damping tail: scrutinizing the tension between the ACT and SPT experiments.

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The Atacama Cosmology Telescope (ACT) and the South Pole Telescope (SPT) have recently provided new, very precise measurements of the cosmic microwave background (CMB) anisotropy damping tail. The values of the cosmological parameters inferred from these measurements, while broadly consistent with the expectations of the standard cosmological model, are providing interesting possible indications for new physics that are definitely worth of investigation. The ACT results, while compatible with the standard expectation of three neutrino families, indicate a level of CMB lensing, parametrized by the lensing amplitude parameter A_L, that is about 70% higher than expected. If not a systematic, an anomalous lensing amplitude could be produced by modifications of general relativity or coupled dark energy. Vice-versa, the SPT experiment, while compatible with a standard level of CMB lensing, prefers an excess of dark radiation, parametrized by the effective number of relativistic degrees of freedom $N_{\rm eff}$. Here we perform a new analysis of these experiments allowing simultaneous variations in both these non-standard parameters. We also combine these experiments, for the first time in the literature, with the recent WMAP9 data, one at a time. Including the Hubble Space Telescope (HST) prior on the Hubble constant and information from baryon acoustic oscillations (BAO) surveys provides the following constraints from ACT: $N_{\rm eff} = 3.23 \pm 0.47$, $A_L = 1.65 \pm 0.33$ at 68% c.l., while for SPT we have $N_{\rm eff} = 3.76 \pm 0.34$, $A_L = 0.81 \pm 0.12$ at 68% c.l.. In particular, the A_L estimates from the two experiments, even when a variation in $N_{\rm eff}$ is allowed, are in tension at more than 95% c.l..

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I. INTRODUCTION

The new measurements of the Cosmic Microwave Background (CMB) anisotropies provided by the Atacama Cosmology Telescope (ACT) [1] and the South Pole Telescope (SPT) [2] have both provided new and exquisitely precise observations of the CMB damping tail.

This angular region of the CMB angular spectra, corresponding to the multipole range going from $\ell \sim 700$ up to $\ell \sim 3000$, plays a key role in the determination of crucial parameters like the relativistic number of degrees of freedom $N_{\rm eff}$, the primordial Helium abundance Y_p and the running $dn/d\ln k$ of the scalar spectral index.

Among those parameters, Y_p can be determined unambigously assuming standard Big Bang Nucleosynthesis (and thus does not represent a free parameter of the theory), while $dn/d\ln k$ is expected to be negligible in most inflationary models. On the other hand, the effective number of relativistic degrees of freedom $N_{\rm eff}$ practically parametrizes the energy density of relativistic particles in the early Universe. In the standard scenario, with the three active relativistic neutrino species, a value of $N_{\rm eff} = 3.046$ is expected [3]. Deviations from this value due to a non-vanishing neutrino chemical potential are possible but bound to be small, especially in light of the recent evidences for a large value of the neutrino mixing angle θ_{13}, see e.g. [4, 5]. Thus a detection of $N_{\rm eff} \neq 3.046$ would point to the presence of physics beyond the standard model of particle physics, like the existence of a yet unknown particle, e.g., a sterile neutrino.

The damping tail is not only affected by those parameters but also by other physical effects generally taking place at a much later epoch, well after recombination. These includes, for example, the extragalactic foreground emission of point sources, radio galaxies, the Sunyaev-Zel'dovich effect and similar unresolved backgrounds. These foregrounds can however be well identified by their spectral and angular dependence and have in general a minimal correlation with the cosmological parameters.

More importantly, the CMB damping tail is affected by the lensing of CMB photons by dark matter clumps along the line of sight. This effect is linear, can be computed precisely and depends on the same cosmological parameters that affect the primary CMB spectrum. However, the lensing amplitude is strictly dependent from the growth of perturbations. This quantity can be significant different if, for example, general relativity is not the correct theory to describe gravity at the very large scales. If the accelerated expansion of our universe is indeed provided not by a dark energy component but by modified gravity, the perturbation growth could be dramatically different and change the expectations of lensing (see, for example [6] and references therein). In order to test the

correct amplitude of the lensing signal, one can introduce a calibration parameter A_L, as in [7], that scales the lensing potential in such a way that $A_L = 0$ corresponds to the complete absence of lensing, while $A_L = 1$ is the expected lensed result assuming general relativity. A robust detection of A_L being different from unity would hint to the fact that general relativity is not the correct theory to describe gravity at the cosmological scales.

The new ACT and SPT data, while broadly consistent with the expectations of the standard ΛCDM scenario, are indeed providing interesting hints for deviations from the simplest ΛCDM model when combined with the results from 7 years of observations from the WMAP satellite (WMAP7, [12]).

The SPT experiment, for example, is confirming an indication for a value for $N_{\rm eff} > 3.046$. This indication, already present in the previous data release (see e.g. [8], [9] and [10]), is marginal when considering only the WMAP7+SPT data with $N_{\rm eff} = 3.62 \pm 0.48$ at 68% c.l.. However, it is more significant when the SPT data is combined with the measurement of the Hubble constant $H_0 = 73.8 \pm 2.4 {\rm km\,s^{-1}\,Mpc^{-1}}$ from the Hubble Space Telescope (HST) [11] and with information from Baryonic Acoustic Oscillation (BAO) data (see Table 4 in [2]), yielding a final value of $N_{\rm eff} = 3.71 \pm 0.35$.

At the same time, the ACT collaboration presented a similar analysis obtaining different results. In particular, the WMAP7+ACT data alone constrain the neutrino number to be $N_{\rm eff} = 2.78 \pm 0.55$, i.e. perfectly consistent with the standard three-neutrino framework. When the ACT data is combined with HST and BAO data the value is higher, $N_{\rm eff} = 3.52 \pm 0.39$, but still consistent with three neutrinos families (see Table III in [1]).

Interestingly, this is not the only tension between the two datasets. If we now consider the results on the lensing amplitude parameter, the SPT dataset is fully compatible with the standard expectation, with $A_L = 0.86^{+0.15}_{-0.13}$ at 68% c.l. (see [13]), while the ACT data suggest a 2σ deviation from the standard expectation, with $A_L = 1.70 \pm 0.38$ at 68% c.l..

In this brief paper we further investigate these discrepancies by improving these analyses in two ways. First of all, we perform our analyses allowing *both* $N_{\rm eff}$ and A_L parameters to vary at the same time. As we will see, this let to better identify the tension between the two experiments. Secondly, we add the recent dataset from nine years of observations coming from the WMAP satellite as in [14]. Both ACT and SPT teams used the previous 7-year WMAP dataset in their papers and some, albeit small, differences are present when the updated dataset is considered.

Our paper is simply organized as follows: in the next section we describe the analysis method, in Section III we present our results and in Section IV we derive our conclusions.

II. DATA ANALYSIS METHOD

Our analysis is based on a modified version of the public CosmoMC [15] Monte Carlo Markov Chain code. We consider the following CMB data: WMAP9 [14], SPT [2], ACT [1] including measurements up to a maximum multipole number of $l_{\rm max} = 3750$. For all these experiments we make use of the publicly available codes and data. For the ACT experiment we use the "lite" version of the likelihood [22]. Since ACT and SPT dataset are providing different results on the parameters, we will consider them separately. Thus our basic CMB-only datasets consist of the WMAP9+ACT and WMAP9+SPT data.

We also consider the effect of including additional dataset to the basic datasets just described. Consistently with the measurements of the HST [11], we consider a gaussian prior on the Hubble constant $H_0 = 73.8 \pm 2.4\,{\rm km\,s^{-1}\,Mpc^{-1}}$. We also include information from measurements of baryonic acoustic oscillations (BAO) from galaxy surveys. Here we follow the approach presented in [14] combining four datasets: 6dFGRS from [16], SDSS-DR7 from [17], SDSS-DR9 from [18] and WiggleZ from [19].

We sample the standard six-dimensional set of cosmological parameters, adopting flat priors on them: the baryon and cold dark matter densities $\Omega_{\rm b}h^2$ and $\Omega_{\rm c}h^2$, the ratio of the sound horizon to the angular diameter distance at decoupling θ, the optical depth to reionization τ, the scalar spectral index n_s, the overall normalization of the spectrum A_s at $k = 0.002$ Mpc^{-1}.

Since the ACT and SPT data are showing indications for deviations from their standard values, we also consider variations in the effective number of relativistic degrees of freedom $N_{\rm eff}$ and in the lensing amplitude parameter A_L as defined in [7], that simply rescales the lensing potential:

$$C_\ell^{\phi\phi} \rightarrow A_L C_\ell^{\phi\phi} \quad (1)$$

where $C_\ell^{\phi\phi}$ is the power spectrum of the lensing field. We take flat priors on all the parameters; in particular, we take $1 < N_{\rm eff} < 10$ and $0 < A_L < 4$.

In our basic runs, we do not consider the effect of massive neutrinos. We perform additional runs in which we allow for a non-vanishing neutrino mass, parametrized by means of the neutrino fraction $f_\nu \equiv \Omega_\nu/\Omega_c$. We always assume standard Big Bang Nucleosynthesis, so that the Helium abundance Y_p is uniquely determined by the values of $\Omega_b h^2$ and $N_{\rm eff}$.

Finally, in order to assess the convergence of our MCMC chains, we compute the Gelman and Rubin $R-1$ parameter demanding that $R - 1 < 0.03$.

III. RESULTS

As stated in the previous section, we consider the ACT and SPT datasets separately. We therefore

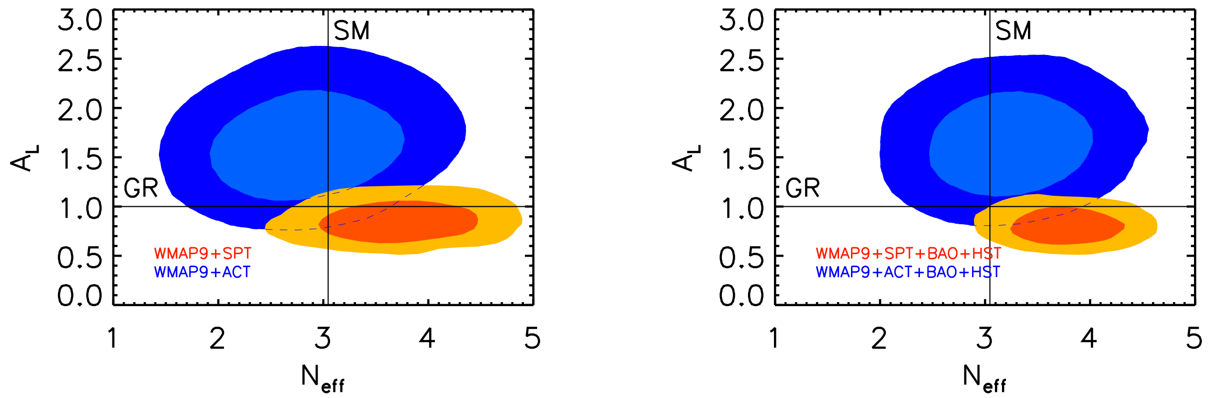

FIG. 1. Constraints in the A_L - $N_{\rm eff}$ plane from a CMB only analysis (left panel) and including the HST prior and BAO (right panel). The blue contour includes the ACT data while the red contour refers to the SPT data. The line at $A_L = 1$ indicates the standard expectations based on General Relativity. The line at $N_{\rm eff} = 3.046$ indicates the prediction from the standard model with three neutrino flavours.

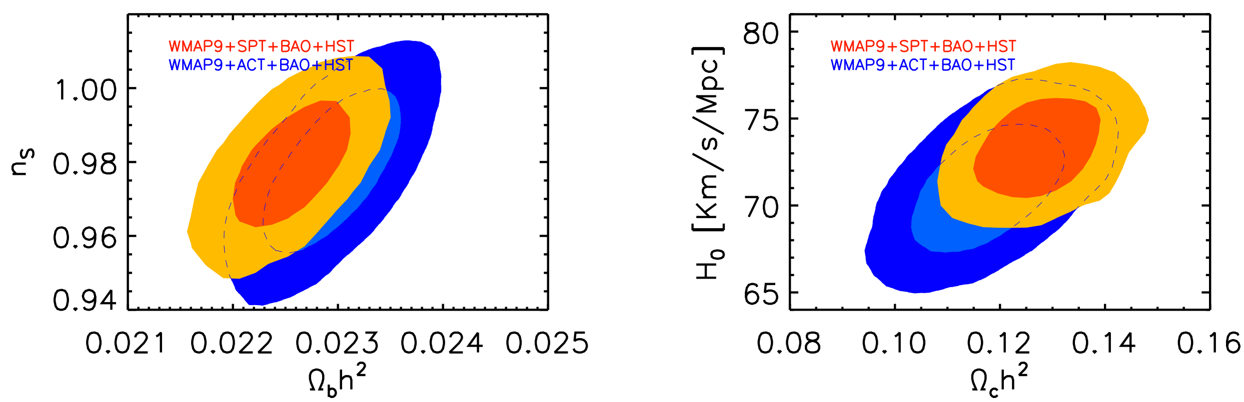

FIG. 2. Constraints in the $\Omega_b h^2$ - n_s plane (left panel) and on the $\Omega_c h^2$-H_0 plane (right panel) from ACT (blue contours) and SPT (orange contours) including WMAP9, HST and BAO data. The ACT-SPT tension is less pronounced for these parameters.

perform the following four analyses: WMAP9+ACT, WMAP9+ACT+HST+BAO, WMAP9+SPT, and WMAP9+SPT+HST+BAO.

In Table I we report the constraints on the considered parameters from each run. As we can see, the ACT and SPT are providing significantly different constraints on the $N_{\rm eff}$ and A_L parameters.

In order to further investigate this discrepancy, we plot in figure 1 the 2-D constraints on the $N_{\rm eff}$ vs A_L plane for the CMB only case and for the CMB+HST+BAO analysis.

As we can see, a tension is clearly present since the central values for $N_{\rm eff}$ and A_L obtained from WMAP9+ACT analysis are outside the 95% confidence level of the WMAP9+SPT and vice-versa. Namely, the ACT dataset is pointing towards a value of $N_{\rm eff}$ fully consistent with the standard scenario of $N_{\rm eff} = 3.046$, while (as it can be seen from Table 1 and Figure 1), preferring at the same time an exotic high value for the lensing potential, with A_L larger than unity at more than 95% c.l. when the BAO and HST datasets are included. Considering the 95% confidence levels we found $A_L = 1.64^{+0.63}_{-0.56}$ for the WMAP+ACT analysis and $A_L = 1.65^{+0.56}_{-0.52}$ for the WMAP+ACT+BAO+HST.

The situation is opposite for the SPT data: while SPT is fully consistent with $A_L = 1$, $N_{\rm eff}$ is constrained to a larger value than the standard expectation. When also the HST and BAO data are included, we see that not only a value of $N_{\rm eff} > 3.04$ is suggested at more than 95% c.l., but also a value of A_L smaller than one is suggested at about 68% c.l..

In particular, we found that $A_L < 1.07$ at 95% c.l. from WMAP9+SPT+BAO+HST while $A_L > 1.13$ at 95% c.l. from WMAP9+ACT+BAO+HST, i.e. for the

Parameters	**SPT**+WMAP9	**ACT**+WMAP9	**SPT**+WMAP9+HST+BAO	**ACT**+WMAP9+HST+BAO
$\Omega_b h^2$	0.02264 ± 0.00051	0.02283 ± 0.00052	0.02255 ± 0.00036	0.02294 ± 0.00042
$\Omega_c h^2$	0.1232 ± 0.0080	0.110 ± 0.010	0.1274 ± 0.0075	0.1178 ± 0.0094
θ	1.0415 ± 0.0012	1.0412 ± 0.0025	1.0413 ± 0.0012	1.0400 ± 0.0024
τ	0.088 ± 0.014	0.090 ± 0.014	0.085 ± 0.013	0.090 ± 0.014
n_s	0.982 ± 0.018	0.969 ± 0.019	0.979 ± 0.011	0.978 ± 0.014
$N_{\rm eff}$	3.72 ± 0.46	2.85 ± 0.56	3.76 ± 0.34	3.23 ± 0.47
A_L	0.85 ± 0.13	1.64 ± 0.36	0.81 ± 0.12	1.65 ± 0.33
H_0[km/s/Mpc]	74.6 ± 3.7	69.9 ± 3.7	73.3 ± 1.8	71.1 ± 2.4
$\log(10^{10} A_s)$	3.169 ± 0.048	3.174 ± 0.045	3.185 ± 0.034	3.174 ± 0.037
Ω_Λ	0.736 ± 0.023	0.728 ± 0.025	0.721 ± 0.015	0.721 ± 0.017
$\Omega_{\rm m}$	0.264 ± 0.023	0.272 ± 0.025	0.279 ± 0.015	0.279 ± 0.017
Age/Gyr	13.14 ± 0.43	13.90 ± 0.55	13.12 ± 0.28	13.55 ± 0.41
D_{3000}^{SZ}	5.8 ± 2.4	—	5.8 ± 2.5	—
D_{3000}^{CL}	5.2 ± 2.1	—	5.3 ± 2.1	—
D_{3000}^{PS}	19.6 ± 2.5	—	19.5 ± 2.5	—
A_{SZ}	—	1.00 ± 0.57	—	0.91 ± 0.57
$\chi^2_{\rm min}$	3806.25	3798.83	3808.06	3800.59

TABLE I. Cosmological parameter values and 68% confidence level errors. The SPT and ACT datasets produce different values for some of the parameters, most notably $N_{\rm eff}$ and A_L.

Parameters	**SPT** +WMAP9+HST+BAO	**SPT** +WMAP9+HST+BAO	**ACT** +WMAP9+HST+BAO	**ACT** +WMAP9+HST+BAO
$\Omega_b h^2$	0.02278 ± 0.00036	0.02274 ± 0.00037	0.02289 ± 0.00042	0.02303 ± 0.00043
$\Omega_c h^2$	0.1305 ± 0.0084	0.1310 ± 0.0082	0.1163 ± 0.0087	0.1193 ± 0.0097
θ	1.0412 ± 0.0011	1.0412 ± 0.0011	1.0402 ± 0.0023	1.0402 ± 0.0023
τ	0.089 ± 0.013	0.089 ± 0.013	0.094 ± 0.014	0.091 ± 0.014
n_s	0.989 ± 0.012	0.987 ± 0.012	0.976 ± 0.014	0.981 ± 0.014
$N_{\rm eff}$	3.89 ± 0.38	3.88 ± 0.37	3.09 ± 0.43	3.28 ± 0.48
$\Sigma m_\nu [eV]$	0.40 ± 0.22	< 0.77 (95% c.l.)	< 0.40 (95% c.l.)	< 0.53 (95% c.l.)
A_L	1.00	0.90 ± 0.15	1.00	1.78 ± 0.38
H_0[km/s/Mpc]	72.4 ± 2.0	72.5 ± 1.9	69.3 ± 2.4	70.1 ± 2.5
$\log(10^{10} A_s)$	3.156 ± 0.034	3.166 ± 0.036	3.177 ± 0.036	3.162 ± 0.037
Ω_Λ	0.707 ± 0.020	0.707 ± 0.019	0.710 ± 0.019	0.710 ± 0.020
$\Omega_{\rm m}$	0.293 ± 0.020	0.293 ± 0.019	0.290 ± 0.019	0.290 ± 0.020
Age/Gyr	13.12 ± 0.29	13.10 ± 0.28	13.75 ± 0.40	13.59 ± 0.42
D_{3000}^{SZ}	5.8 ± 2.4	6.1 ± 2.4	—	—
D_{3000}^{CL}	5.3 ± 2.2	5.2 ± 2.1	—	—
D_{3000}^{PS}	19.3 ± 2.4	19.3 ± 2.5	—	—
A_{SZ}	—	—	0.97 ± 0.57	0.97 ± 0.57
$\chi^2_{\rm min}/2$	3808.0	3807.5	3802.47	3800.59

TABLE II. Cosmological parameter values and 68% confidence level errors for the analysis that considers massive neutrinos. As we can see, varying A_L strongly affects the constraints on the total neutrino mass. Vice-versa, allowing for a neutrino mass renders the SPT value for A_L more compatible with the standard value while exacerbates the problem for the ACT dataset.

lensing parameter the SPT and ACT datasets are providing constraints that are in disagreement at more than 95% c.l..

It is interesting to note that the tension between the ACT and SPT datasets is clearly not limited to A_L or $N_{\rm eff}$: also the constraints on H_0, n_s, $\Omega_b h^2$ and $\Omega_c h^2$ appear as quite different. The discrepancy is however less significant since the central values are inside the 95% confidence level of each analysis (see Figure 2).

The results discussed so far are relative to the analysis in which all neutrinos are considered as relativistic and massless. Since the SPT dataset is claiming a detection at 95% c.l. for a neutrino mass with $\Sigma m_\nu = 0.48 \pm 0.21$ in a WMAP7+SPT+BAO+HST analysis (see [2]), it is clearly interesting to consider also massive neutrinos.

In table II we present the constraint on cosmological parameters from the WMAP9+SPT+HST+BAO and WMAP9+ACT+HST+BAO datasets respectively when variation in the neutrino masses are included in two cases: varying A_L and fixing $A_L = 1$.

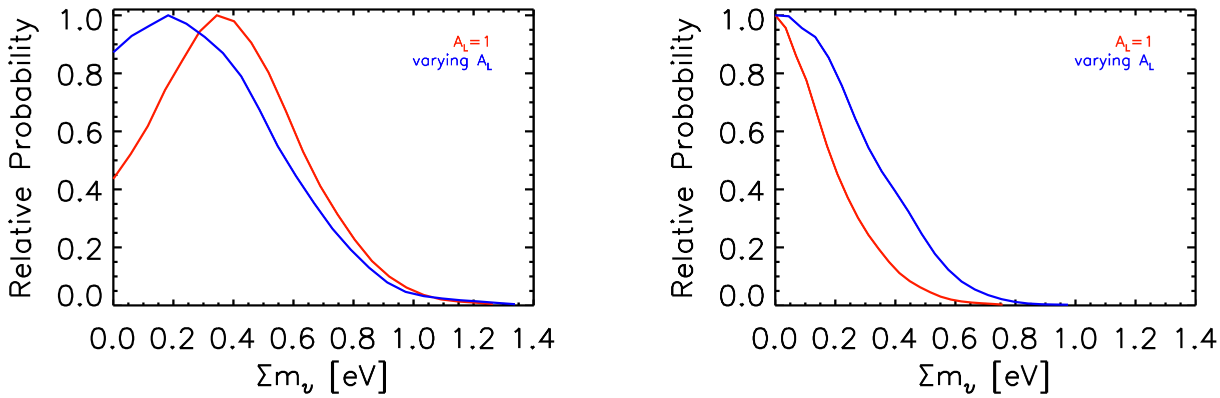

FIG. 3. Posterior distribution function for the total neutrino mass parameter Σm_ν from a SPT+WMAP+BAO+HST analysis (left panel) and ACT+WMAP+BAO+HST (right panel) in the case of fixing lensing to $A_L = 1$ and letting it to vary. As we can see, if we let the A_L parameter to vary the small indication for a neutrino mass from the SPT analysis vanishes. At the same time, letting the A_L parameter to vary weakens the constraints from ACT.

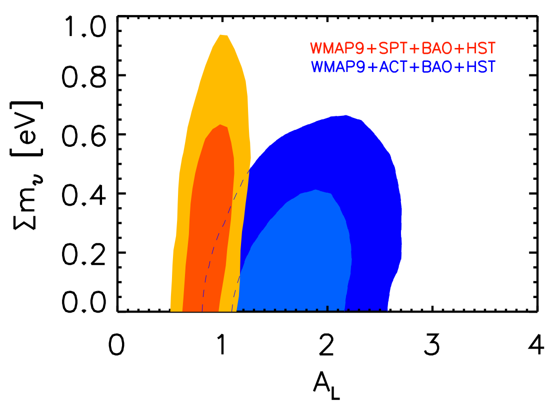

FIG. 4. Constraints in the A_L vs Σm_ν plane for the SPT+WMAP+BAO+HST and ACT+WMAP+BAO+HST datasets. A degeneracy is present between the two parameters: larger values for A_L let larger neutrino masses to be more consistent with the data. The SPT indication for a neutrino mass is driven by the low value of A_L obtained in the neutrino massless case.

As we can see, while the ACT dataset does not favour the presence of neutrino masses, the SPT dataset gives $\Sigma m_\nu = 0.40 \pm 0.22$ at 68% c.l. in the case of $A_L = 1$ and a lower limit limit $\Sigma m_\nu > 0.04eV$ at 95% c.l.. This is consistent with the results reported in [2] considering the different WMAP and BAO datasets. However, when A_L is let to vary, the evidence for a neutrino mass vanishes, as also clearly see in Figure 3.

We can better see what is happening by looking at the constraints in the A_L vs Σm_ν plane in Figure 4. As we can see, there is a degeneracy between A_L and Σm_ν. Namely, a larger value of Σm_ν decreases the lensing signal and can be compensated with a larger A_L. Since the SPT dataset is preferring smaller values of the lensing parameter, an analysis with $A_L = 1$ forces the neutrino mass to be more consistent with the data.

Is also worth mentioning that including a neutrino mass exacerbates the lensing problem for ACT. The lensing parameter A_L is even higher when massive neutrinos are considered (see Table II).

IV. DISCUSSION

In this paper we have pointed out a tension between the parameter values estimated from the recent ACT and SPT datasets. This discrepancy, albeit not significantly more than the 95% confidence level, is indicating the possible presence of systematics in at least one of the two datasets. The SPT experiment is confirming the previous indications for a "dark radiation" component with $N_{\rm eff} = 3.76 \pm 0.34$ at 68% c.l.; in particular we have found that $N_{\rm eff} > 3.08$ at more than 95% c.l.. This result is clearly interesting since, if confirmed with larger significance by future data, could be possibly explained by several physical mechanisms, and would hint to new physics. In fact, the most conventional explanation for $N_{\rm eff} > 3.046$ would be the presence of non-vanishing neutrino chemical potentials, i.e. of a cosmological lepton asymmetry. However, as it was shown in Refs.[4, 5] through the analysis of BBN and CMB data, lepton asymmetries can at most account for $N_{\rm eff} \simeq 3.1$, given the recent measurements of the neutrino mixing angle θ_{13} by the Daya Bay [23] and RENO experiments [24] that exclude a zero value for θ_{13} with high significance.

Thus, if confirmed, a value of $N_{\rm eff}$ larger than 3.1 definitely requires some non-conventional explanation. Sterile neutrinos, extra dimensions, gravity waves or non-

standard neutrino decoupling could all be viable new mechanisms to explain a value of $N_{\rm eff}$ larger than the standard value (see e.g. [20]).

The ACT experiment is, on the contrary, fully consistent with $N_{\rm eff} = 3.04$ even when the HST and BAO dataset are included. There is clearly no evidence for dark radiation from ACT; moreover the case for a fourth, massless neutrino, such that $N_{\rm eff} \simeq 4$ is excluded at more than 95% c.l. when only CMB data is considered. In particular, we found at 95% c.l. that $N_{\rm eff} = 2.85^{+0.95}_{-0.91}$ for WMAP9+ACT and $N_{\rm eff} = 3.23^{+0.77}_{-0.76}$ for WMAP9+ACT+BAO+HST. It is interesting to notice that our WMAP9+ACT+BAO+HST run provides the constraint $N_{\rm eff} = 3.23 \pm 0.47$ while a similar analysis from ACT gives $N_{\rm eff} = 3.52 \pm 0.39$ but with $A_L = 1$ and with the WMAP7 data.

However, ACT presents a value for the lensing parameter that is off by more than 95% from the expected value $A_L = 1$. This result is probably more difficult to explain from a physical point of view than a deviation in $N_{\rm eff}$ and calls for more drastic changes in the cosmological model. A possible way to enhance the lensing signal is to assume a modification to general relativity. $f(R)$ models as those investigated in [6] could in principle enhance the lensing signal, even if it is not clear if they could enhance it by $\sim 70\%$ and be at the same time consistent with other independent limits coming from tests of general relativity, like, e.g. solar system tests. Other possible explanations include coupled dark energy models (see e.g. [21] and references therein). Clearly, it may be that the ACT lensing signal is on the contrary simply produced by some unknown systematic as also suggested by the inclusion of the ACT deflection spectrum data, that shifts the value to $A_L = 1.3 \pm 0.23$ ([1]). However it is not clear if this systematic could also affect the ACT constrain on $N_{\rm eff}$ and other parameters.

The SPT experiment is compatible with $A_L = 1$ but is suggesting a value $A_L < 1$ at about 68% c.l. especially when also the BAO and HST data are included.

The ACT and SPT measurements of A_L, even if we consider variation in the $N_{\rm eff}$ parameter, are in disagreement at more than 95% c.l..

Finally, we have also considered variation in the neutrino mass and show that the current indication for a neutrino mass from the SPT+WMAP9+BAO+HST run is driven by the lower lensing amplitude measured by SPT. If we let the lensing parameter A_L to vary the indication for a neutrino mass vanishes. Moreover, we have shown that the inclusion of a neutrino mass exacerbates the lensing problem for the ACT data with the A_L even more discrepant with the $A_L = 1$ case. The constraints on the neutrino mass from ACT are weaker when variations in A_L are considered.

In this paper we have only considered a limited set of parameters but the tension between SPT and ACT is present also in other, relevant, parameters. The SPT dataset, for example, shows a preference for a negative running of the inflationary spectral index at more than 95% c.l. while the ACT data is consistent with a zero running in between the 95% c.l. (see Figure 11 of [1]).

We therefore conclude that the whole picture is, at the moment, stimulating and puzzling at the same time. The ACT and SPT collaborations have provided an impressive confirmation of the theoretical expectations concerning the damping tail of the CMB anisotropy spectrum. However they are also suggesting interesting deviations from the standard picture, that are unfortunately very different and opposite. It will be the duty of future reanalyses of the ACT and SPT data (possibly stemming from within the collaborations themselves) and experiments (e.g., Planck) to finally decide whether what ACT and SPT are currently seeing is due to dark radiation, dark gravity or more simply to an unidentified (hence, dark too) experimental systematic effect.

V. ACKNOWLEDGEMENTS

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[1] J. L. Sievers, R. A. Hlozek, M. R. Nolta, V. Acquaviva, G. E. Addison, P. A. R. Ade, P. Aguirre and M. Amiri *et al.*, arXiv:1301.0824 [astro-ph.CO].

[2] Z. Hou, C. L. Reichardt, K. T. Story, B. Follin, R. Keisler, K. A. Aird, B. A. Benson and L. E. Bleem *et al.*, arXiv:1212.6267 [astro-ph.CO].

[3] G. Mangano, G. Miele, S. Pastor, T. Pinto, O. Pisanti and P. D. Serpico, Nucl. Phys. B **729**, 221 (2005) [hep-ph/0506164].

[4] G. Mangano, G. Miele, S. Pastor, O. Pisanti and S. Sarikas, Phys. Lett. B **708**, 1 (2012) [arXiv:1110.4335 [hep-ph]].

[5] E. Castorina, U. Franca, M. Lattanzi, J. Lesgourgues, G. Mangano, A. Melchiorri and S. Pastor, Phys. Rev. D **86**, 023517 (2012) [arXiv:1204.2510 [astro-ph.CO]].

[6] E. Calabrese, A. Cooray, M. Martinelli, A. Melchiorri, L. Pagano, A. Slosar and G. F. Smoot, Phys. Rev. D **80** (2009) 103516 [arXiv:0908.1585 [astro-ph.CO]].

[7] E. Calabrese, A. Slosar, A. Melchiorri, G. F. Smoot and O. Zahn, Phys. Rev. D **77** (2008) 123531 [arXiv:0803.2309 [astro-ph]].

[8] Z. Hou, R. Keisler, L. Knox, M. Millea and C. Reichardt, arXiv:1104.2333 [astro-ph.CO].

[9] M. Archidiacono, E. Calabrese and A. Melchiorri, Phys. Rev. D **84** (2011) 123008 [arXiv:1109.2767 [astro-ph.CO]].

[10] E. Giusarma, M. Corsi, M. Archidiacono, R. de Putter, A. Melchiorri, O. Mena and S. Pandolfi, Phys. Rev. D **83** (2011) 115023 [arXiv:1102.4774 [astro-ph.CO]].

[11] A. G. Riess, L. Macri, S. Casertano, H. Lampeitl, H. C. Ferguson, A. V. Filippenko, S. W. Jha and W. Li *et al.*, Astrophys. J. **730**, 119 (2011) [Erratum-ibid. **732**, 129 (2011)] [arXiv:1103.2976 [astro-ph.CO]].

[12] E. Komatsu *et al.*, Astrophys. J. Supp. **192**, 18 (2011) [arXiv:1001.4538 [astro-ph.CO]].

[13] K. T. Story, C. L. Reichardt, Z. Hou, R. Keisler, K. A. Aird, B. A. Benson, L. E. Bleem and J. E. Carlstrom *et al.*, arXiv:1210.7231 [astro-ph.CO].

[14] G. Hinshaw, D. Larson, E. Komatsu, D. N. Spergel, C. L. Bennett, J. Dunkley, M. R. Nolta and M. Halpern *et al.*, arXiv:1212.5226 [astro-ph.CO].

[15] A. Lewis and S. Bridle, Phys. Rev. D **66**, 103511 (2002) [arXiv:astro-ph/0205436].

[16] Beutler, F., et al., Montly Notices of the Royal Astronomical Society, 416, 3017, 2011

[17] Padmanabhan, N., Xu, X., Eisenstein, D. J., Scalzo, R., Cuesta, A. J., Mehta, K. T., & Kazin, E. 2012, ArXiv e-prints, arXiv:1202.0090

[18] L. Anderson, et al. 2012, ArXiv e-prints, arXiv:1203.6594

[19] C. Blake et al., Montly Notices of the Royal Astronomical Society, 425, 405, 2012

[20] S. Hannestad, A. Mirizzi, G. G. Raffelt and Y. Y. Y. Wong, JCAP **1008** (2010) 001 [arXiv:1004.0695 [astro-ph.CO]]; A. Melchiorri, O. Mena and A. Slosar, Phys. Rev. D **76** (2007) 041303 [arXiv:0705.2695 [astro-ph]]; T. L. Smith, E. Pierpaoli and M. Kamionkowski, Phys. Rev. Lett. **97** (2006) 021301 [arXiv:astro-ph/0603144]; P. Binetruy, C. Deffayet, U. Ellwanger and D. Langlois, Phys. Lett. B **477** (2000) 285 [arXiv:hep-th/9910219]; T. Shiromizu, K. i. Maeda and M. Sasaki, Phys. Rev. D **62** (2000) 024012 [arXiv:gr-qc/9910076]; S. Mukohyama. Phys. Lett. B **473**, 241-245 (2000), doi = "10.1016/S0370-2693(99)01505-1".

[21] M. Martinelli, L. Lopez Honorez, A. Melchiorri and O. Mena, Phys. Rev. D **81** (2010) 103534 [arXiv:1004.2410 [astro-ph.CO]].

[22] J. Dunkley, E. Calabrese, J. Sievers, G. E. Addison, N. Battaglia, E. S. Battistelli, J. R. Bond and S. Das *et al.*, arXiv:1301.0776 [astro-ph.CO].

[23] F. P. An *et al.* [DAYA-BAY Collaboration], Phys. Rev. Lett. **108**, 171803 (2012) [arXiv:1203.1669 [hep-ex]].

[24] J. K. Ahn *et al.* [RENO Collaboration], Phys. Rev. Lett. **108**, 191802 (2012) [arXiv:1204.0626 [hep-ex]].